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Life cycle assessment of carbon dioxide for different arboricultural practices in Los Angeles, CA

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ABSTRACT

Although the arboriculture industry plants and maintains trees that remove CO_2 from the atmosphere, it uses heavy-duty equipment and vehicles that release more CO_2 per year than other similar-sized industries in the service sector. This study used lifecycle assessment to compare CO_2 emissions associated with different decisions by arborists to the amount of CO_2 sequestered over 50 years for California sycamore (*Platanus racemosa*) planted in Los Angeles, CA. Scenarios examined effects of equipment and vehicle choices, different operational efficiencies, amounts of irrigation water applied and the fate of wood residue from pruning and tree removal. For the Highest Emission Case, total emissions (9.002 t) exceeded CO_2 stored (−7.798 t), resulting in net emissions of 1.204 t. The Lowest Emission Case resulted in net removal of −3.768 t CO_2 over the 50-year period. Tree selection and irrigation water management were key leverage points in Los Angeles. Converting residue from the removed tree to wood products resulted in substantially lower net CO_2 emissions than did converting it into bioenergy or mulch. Although emissions from vehicles and equipment accounted for less than 6% of the CO_2 stored in the tree, substantial reductions are achievable. Arborists can reduce CO_2 emissions threefold by converting from high- to low-emitting equipment and vehicles. By reducing travel distances and equipment run-times, twofold emission reductions are possible. Reducing the amount of aboveground biomass pruned from 20% to 10% every five years lowered pruning emissions fivefold.

Introduction

The Intergovernmental Panel on Climate Change's Fifth report (Field et al., 2014) indicates that the effects of a changing climate are now widely evident. Very heavy precipitation events and lengthy dry spells are among trends likely to continue and increasingly impact the health and function of urban forests. The arboriculture industry is involved in maintaining carbon stored in existing trees, as well as drawing additional carbon dioxide (CO_2) from the atmosphere through tree planting (McPherson, 1994; Nowak et al., 2013). Furthermore, trees that modify irradiance and building microclimates can reduce energy used to heat and cool structures, thereby lowering CO_2 emissions from fossil fuel combustion (Akbari, 2002; Simpson and McPherson, 1998).

Because of the difficulty and high cost of permanently storing CO_2 in trees, no urban tree planting projects have been registered by the Climate Action Reserve, whose credits can be sold in the voluntary market (Climate Action Reserve, 2010). Given the many challenges to offsetting emissions through tree planting and maintenance, it is argued that the best option is to avoid emissions in the first place (Mackey, 2014). For arborists, fossil fuel emissions can be reduced directly by shrinking the carbon footprint of their operations through use of low-emitting engines and more efficient practices. Arborists can indirectly reduce emissions by reducing irrigation when fossil energy is used to pump, treat and deliver water, and by using wood residue as a source of electricity in bioenergy plants (McPherson and Kendall, 2014). Also, biogenic emissions from decomposition of wood chips from pruned and removed trees can be delayed by turning the biomass into products such as benches, tables, flooring and crafted objects (Bratkovich, 2001).

Although the industry uses heavy-duty trucks and equipment such as cranes, stump grinders, chippers and aerial lifts, the few studies conducted to date suggest that tree planting and maintenance emissions are relatively small, less than 10% of the amount of atmospheric CO_2 reduction from biogenic storage and avoided

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emissions (McPherson and Simpson, 1999; Sola et al., 2007; Strohbach et al., 2012). However, these studies did not include the full scope of emissions associated with vehicles, equipment and materials at each life stage. For instance, emissions associated with tree production, planting site preparation, the fate of removed biomass and fossil fuels consumed to transport, treat and distribute irrigation water were often omitted.

Using surveys, interviews, field sampling and computer simulation of tree growth and survival over a 40-year time period, McPherson and Kendall (2014) developed the first process-based life cycle inventory (LCI) of CO_2 for a tree planting initiative. Emissions and reductions of CO_2 from storage in the urban forest biomass and avoided emissions from energy savings were simulated for 91,786 trees planted from 2006 to 2010 as part of the Million Tree Los Angeles (MTLA) program (McPherson, 2014). Based on early mortality rates observed in the field, it was estimated that only 30,813 (33.6%) of trees would survive the 40-year span of the study. The total amount of CO_2 emitted (83,408 t) was slightly more than the −77,942 t CO_2 (negative numbers indicate removal from atmosphere) that trees were projected to store in their biomass. Nevertheless, the MTLA program was projected to be a CO_2 sink if 40-year avoided fossil fuel CO_2 emissions from energy savings (−101,679 t) and bioenergy (−1939 t) were realized.

A landmark case study of a United Kingdom tree care company's CO_2 emissions involved two weeks of intensive measurements of fuel use, equipment run-times (RT) and wood biomass harvested (Luck et al., 2014). Vehicle and equipment emissions were 101.2 t per year and indirect emissions from office energy consumption, employee commuting and other sources were 104.1 t per year. They concluded that the arboriculture industry releases seven times more CO_2 per year than other similar-sized industries in the service sector, primarily due to the use of heavy-duty vehicles and equipment.

There are many factors that arborists consider when selecting which vehicles and equipment to use and how they schedule their work. Reducing travel times, improving safety and complying with environmental regulations are issues that influence arborists' decisions. However, benchmarks that establish desirable ranges of CO_2 emissions for activities such as planting, pruning and tree removal are lacking. As concern about the impacts of climate change on humanity and the environment grow, arborists will need science-based data to determine the best way to reduce their carbon footprints. The purpose of this research is to identify "leverage points" where the arborist's decisions can achieve the greatest emission reductions. Four issues are addressed that influence CO_2 emissions:

- Selection of high- and low-emitting vehicles and equipment.
- Operational efficiency of vehicles and equipment.
- Tree irrigation water use.
- Utilization of tree residue as mulch, bioenergy and wood products.

This study extends the MTLA life cycle inventory (LCI) to identify and compare CO_2 emissions at various stages of the life cycle of a typical tree planted in the Los Angeles, CA region. Emissions are projected during the 50-year life of the tree for different scenarios. High and low values are selected to delimit the range of performance observed in the MTLA program and reported in the literature. The estimated magnitudes of CO_2 reductions are compared to identify leverage points. The extent to which different scenarios offset the CO_2 stored by the tree is presented. Because life cycle assessment has not been comprehensively applied to arboriculture, this research contributes new knowledge to the field.

Methods

Goal and scope

The goal of this study is to generate the first detailed estimates of CO_2 emissions attributable to resource deployment and management decisions made by arborists. We expect that this information can be used by the industry as an initial basis for planning and management to reduce CO_2 emissions.

The scope of our analysis constitutes a cradle-to-grave CO_2 assessment that includes fuel use, material inputs and biogenic CO_2 flows for each life stage of the typical tree over a 50-year time horizon. This time horizon corresponds to the expected lifespan of an urban tree not facing arduous growing conditions (Strohbach et al., 2012).

Tree and site

A California sycamore (*Platanus racemosa* Nutt.) is modeled as the representative tree. It is a large-stature deciduous tree native to the region and widely used in landscape plantings. Its growth is modeled using equations developed from intensive measurements on 37 street trees in Claremont, CA (McPherson and Peper, 2012) (see on-line supplementary materials, Table S1).

Aboveground wood volume was calculated using the allometric equation developed from measurements of open growing London planetrees (*Platanus* × *hispanica* Mill. ex Münchh.) in Southern California (Pillsbury et al., 1998) (Table S1). Volume estimates were converted to green (GW) and dry-weight (DW) estimates (Markwardt, 1930) and divided by 78% to incorporate root biomass (Nowak et al., 1994). Dry-weight biomass was converted to carbon (50%) (Leith, 1975), and these values were converted to CO_2. The marginal CO_2 stored in year x was calculated as the total amount stored in year $x+1$ minus the total amount stored in year x.

The climate of Los Angeles is Mediterranean, characterized by hot, dry summers and cool, rainy winters from October through April. Los Angeles has a variety of climate zones because of its proximity to the Pacific Ocean and nearby mountain ranges. Claremont is in the Inland Empire region and 70 km from the ocean. Median annual rainfall in the Claremont area is 397 mm. The average summer maximum temperature seldom exceeds 32 °C, and the average winter minimum seldom drops below 4 °C, although temperatures as high as 42 °C and as low as −3 °C have been recorded (Bernard Field Station Faculty Advisory Committee, 2014).

Life cycle inventory, life stages and emissions scenarios

The LCI model is made up of categories shown in Fig. 1 such as tree production, site inspection, planting, pruning, irrigation, removal, mulch decomposition, bioenergy and wood products. Categories were subdivided into activities for the purposes of developing the LCI. High- and low-emission scenarios were created to represent the range of equipment and vehicles used in the Los Angeles area. Similarly, high- and low-efficiency scenarios were constructed to encompass the range of equipment run-times and vehicle distance traveled per tree site. Information on current equipment and practices was acquired directly from professional arborists (McPherson and Kendall, 2014). The following section describes assumptions used to model CO_2 emissions at each life stage for the scenarios. General methods for calculating emissions from equipment and vehicles follow. Subsequent sections describe the methods used to model irrigation water and wood residue scenarios.

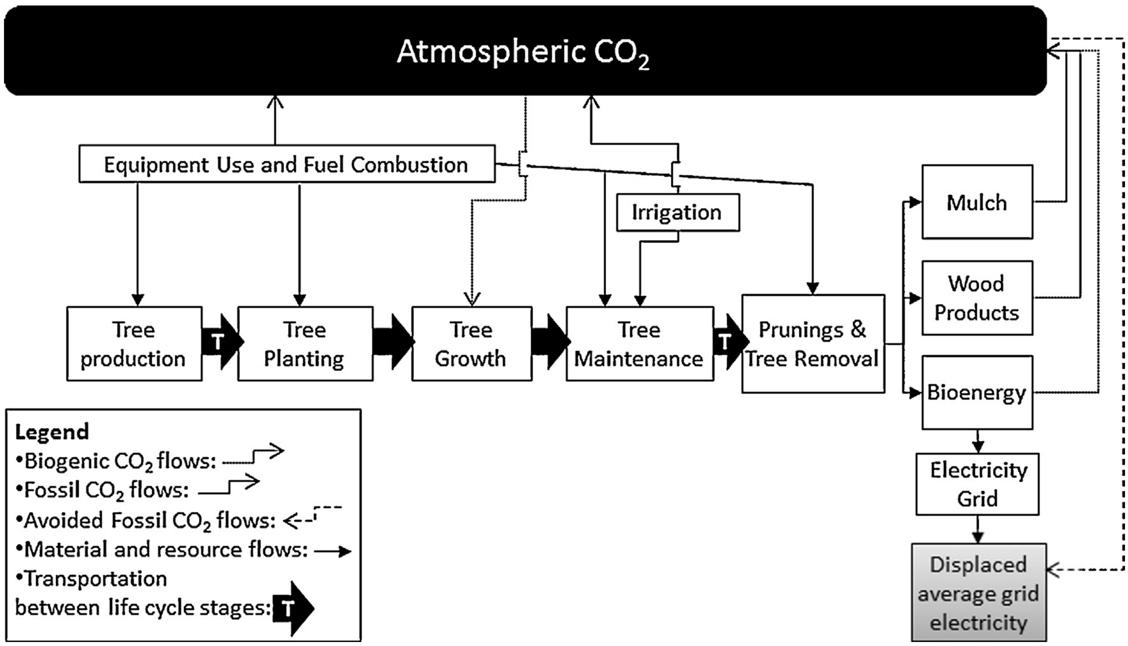

Fig. 1. System diagram.

Tree production

This study applies the emission results from a previous LCI of a tree production system in California to #15 (nominally 15-gallon or 3.8 l in volume, tree about 3.8 cm dbh) trees planted in Los Angeles. The CO_2 emissions were 15.3 kg per tree. Lacking production data from other nurseries, low and high emission values were 10.45 and 25.75 kg per tree, equivalent to one standard deviation of the 15.3 kg value. This assumption implies that high and low values are about 132% and 68% of the 15.3 kg value reported in the literature.

Inspection and site preparation

Prior to planting each site was inspected several times to assess its suitability, mark tree locations and insure that above- and belowground utilities were not at risk. For MTLA plantings in park and street locations, three independent inspections were usually conducted for each tree site. These were conducted by telecommunications, natural gas utility, Los Angeles Department of Water and Power (LADWP) and other agency inspectors. A hybrid passenger vehicle (4.7 $l^{-100\,km}$) and a medium duty truck (22.4 $l^{-100\,km}$) were the assumed transportation for the low- and high-emissions scenarios, respectively (Table S2).

Planting

The low-emissions scenario assumed that trees were planted by hand without imported soil and two vehicles, a light duty truck (15.7 $l^{-100\,km}$) and flatbed truck (22.0 $l^{-100\,km}$), were used. The high-emissions scenario assumed three vehicles were operated: a medium duty truck (17.0 $l^{-100\,km}$), flatbed truck (39.2 $l^{-100\,km}$) and tow truck (39.2 $l^{-100\,km}$) with a Bobcat equipped with an auger (31.17 kilowatt [kW]) (Table S3). The flatbed truck's full-load was 25 container trees (nominally 15-gallon or 3.8 l in volume).

Pruning

The California sycamore tree was assumed to be pruned at five-year intervals, the optimum for most street tree species (Miller and Sylvester, 1981). Cyclic safety pruning of about 10% of the existing tree biomass allows for removal of broken branches and structural flaws (i.e., overlapping branches, codominant leaders) without creating large wounds. Crown reduction pruning occurs when a tree grows too large for the space and results in the removal of large branches. This heavy pruning invigorates growth that is often weakly attached and prone to failure. Large wounds are slow to heal, providing entry points for pests (Harris et al., 1999). For these reasons, most pruning standards suggest that no more than 20% of the tree crown be removed during one prune. Two pruning scenarios were modeled in this study. Safety pruning involved crown raising and cleaning, with 10% of the tree's aboveground woody biomass removed during each pruning event. Crown reduction pruning eliminated 20% of the tree's aboveground woody biomass during each prune to mitigate conflicts with surrounding buildings and to preserve views. Because of the frequent prune cycle it was assumed that the removed wood never became too large to chip.

The low-emissions scenario assumed that the tree was climbed and pruned with an electric chainsaw powered by a backpack battery (36 V). Because of the five-year prune cycle, large branches (>5 cm diameter) never needed to be removed. Residue went into a chipper (37 kW) and was transported to a processing site in a box dump truck (24.8 $l^{-100\,km}$, 5-t green weight [GW] capacity). Clean-up was conducted with an electric blower with backpack battery (0.32 kW) (Table S3). The high-emissions scenario assumed that a bucket truck was used to prune the tree once it exceeded 15 and 30 cm dbh for crown reduction and safety pruning, respectively. Pruning required a 2-stroke chainsaw (4 kW), chipper (104 kW) and blower (2.9 kW). Pruning RTs for the chainsaw were assumed to be the same as for the electric chainsaw in the low-emissions scenario. Three vehicles were used: a medium duty truck (17.0 $l^{-100\,km}$, 5-t GW capacity), box dump truck with chipper (24.8 $l^{-100\,km}$, 5-t GW capacity) and bucket truck (aerial lift, 39.2 $l^{-100\,km}$).

Removal and stump grinding

The analysis assumed that the tree was removed after 50 years and the stump was ground to eliminate root suckers, control disease and make space for replanting. It was assumed that all wood smaller than 30 cm dbh was chipped on site and this accounted for 40%

of the total aboveground biomass. The remaining 60% of biomass was transported 32.2 km round trip to the processing center. The low-emissions scenario assumed that the tree was removed with a medium-sized (61 cm bar) 2-stroke chainsaw (3.65 kW) and chipper (37 kW). The stump was ground with a standard diesel grinder (56 kW) and clean-up was performed with an electric blower with backpack battery (0.32 kW). Three vehicles transported crew and equipment: a medium duty truck (15.7 $l^{-100\,km}$, 5-t GW capacity), box dump truck with chipper (24.8 $l^{-100\,km}$, 5-t GW capacity) and tow truck with stump grinder (16.6 $l^{-100\,km}$). Larger equipment was assumed for the high-emissions scenario: a 2-stroke chainsaw (61 cm bar, 4.5 kW), chipper (104 kW), grinder (131 kW) and blower (2.9 kW). Four vehicles were involved in tree removal and stump grinding: a medium duty truck (22.4 $l^{-100\,km}$, 5-t GW capacity), box dump truck with chipper (24.8 $l^{-100\,km}$, 5-t GW capacity), bucket truck (24.8 $l^{-100\,km}$) and tow truck with stump grinder (39.2 $l^{-100\,km}$). The bucket truck was used once trees exceeded 15 cm dbh.

Operational efficiency scenarios

Research and best management practices (Nowak et al., 2002; O'Brien et al., 1992) have established time ranges for conducting tree care activities on trees of different sizes. By reducing equipment run-times (RT) and the distance traveled to work sites, arborists can improve their operational efficiency (OE), conserve energy and reduce CO_2 emissions. Low, Base and High OE scenarios were developed for each type of equipment (i.e., chainsaw, chipper, aerial lift, blower, bobcat) and activity (i.e., planting, pruning, removal/stump grinding) from previously published performance standards (Tables S4–S6).

The distance traveled per tree was estimated for Low, Base and High OE scenarios developed for each activity. Distances traveled encompassed the lowest and highest values reported for the MTLA program (Table S7). The Base OE scenario assumed that the subject tree was one of the 35 trees planted in two neighborhoods that were approximately 8 km apart. Vehicles traveled 80.5 km round-trip to the two neighborhoods and 32.2 km on-site. On average they traveled 3.2 km per tree planted, pruned and removed. The three inspectors each traveled 24.1 km per tree site. In the Low OE scenario the subject tree was one of the 35 trees planted in scattered locations throughout the city. Vehicles traveled 169 km in a loop to plant and maintain the trees, averaging 4.8 km per tree. Each of the three inspection vehicles traveled 33.8 km per tree. In the High OE scenario the subject tree was one of the 35 trees planted relatively close together in a single park. Vehicles traveled 80.5 km round-trip to the park and 8 km on-site, averaging 1.6 km traveled per tree for planting, pruning and removal activities. Each inspector traveled 14.5 km per tree site.

Equipment and vehicle emissions modeling

Equipment emissions occur during tree production, planting, pruning and removal, chipping and stump grinding. Total annual equipment emissions were calculated as the sum of emissions across all equipment types (Table S8, Eq. (1)). Fuel consumption is directly related to an engine's horsepower (hp), but the load factor (LF) and fuel type also influence CO_2 emissions. Emission factor's (EF) vary for each fuel type (Table S9). The annual RT hours for each equipment type depended on the subject tree's size (dbh) and the OE scenario.

Vehicle emissions were associated with each life stage and calculated annually as the sum of the vehicle emission constant (VEC) times the percentage full load (PFL) for each vehicle (Table S8, Eq. (2)). The VEC (Table S8, Eq. (3)) was calculated for each vehicle type based on distance traveled per tree (km), vehicle fuel efficiency ($l^{-100\,km}$) and EFs for each fuel type. The PFL was calculated as the ratio of the amount of wood residue transported and the vehicle's capacity when fully loaded (Table S8, Eq. (4)). This calculation scaled vehicle emissions to the amount of work done, which increased as the modeled tree grew larger.

Irrigation water scenarios

The Water Use Classification of Landscape Species (WUCOLS) approach (Costello and Jones, 1994) was used to model irrigation water applied annually to the subject tree. Projected irrigation water demand depends on evaporation losses from the tree and soil, as well as irrigation losses (Table S8, Eq. (5)). Species coefficients (K_s) reflect relative evapotranspiration (ET) losses that can range from 0.1 to 0.9 for low and high water use plants (Table S6, Eq. (6)). The K_s for low, medium and high irrigation scenarios were calibrated using daily whole tree transpiration measured for irrigated California sycamore street trees in Los Angeles during July and August (McCarthy and Pataki, 2010). Measured values ranged from 80 to 120 kg day^{-1} for three street trees with an average dbh of 37 cm. These values were converted to daily irrigation volumes using the Claremont-based growth equation for crown diameter to calculate crown projection area (area under the tree's dripline) (168.7 m^2) from dbh for California sycamore (Table S1, Eq. (3)). Daily amounts were annualized based on the proportion of reference ET (ET_0) that occurred for each month at the nearby Glendale weather station (Station ID 133). Annual ET_0 was measured as 126.9 cm in 2013–2014. The calibrated species coefficients for California sycamore were found to be 0.09 (low), 0.12 (moderate) and 0.15 (high). Irrigation efficiency was 80%. LADWP reported an updated CO_2 emissions rate of 0.56 kg CO_2 kl^{-1} for pumping and treating irrigation water (LADWP, 2013).

Wood residue scenarios

Three scenarios (i.e., mulch, bioenergy, lumber) were modeled to explore emissions associated with strategies for utilizing residue from the pruned and removed tree. The first scenario converted wood residue into mulch that was redistributed to planting sites. The dry weight (DW) of wood residue removed during pruning and removal activities was calculated annually. A ratio of 1.56 was used to convert the dry weight of pruned biomass to its equivalent fresh weight of chipped material, based on the average moisture content of 0.56 for hardwoods (Nowak et al., 1994). All pruned wood residue was chipped and transported 32 km round trip (20 miles) from the work site to the processing center in the box dump truck because PFL never exceeded the vehicle's 5-t capacity. The wood residue of the removed tree totaled 3314.7 kg (DW) and exceeded the box dump truck's capacity (PFL = 114%). Therefore, a medium duty truck (15.7 $l^{-100\,km}$, CNG) was required to transport the solid wood residue from the bole and branches greater than 30 cm dbh, separate from the chipped material.

The MTLA LCI (McPherson and Kendall, 2014) reported that the mulch processing site's conversion efficiency was 77%. A light duty truck and a medium duty diesel truck handled the material on-site and a large diesel tub grinder operated 2600 h per year. The biomass processing constant was 13.5 kg CO_2 t^{-1} DW, and the constant for equipment and vehicles was 12.8 and 2.7 kg t^{-1}, respectively. After processing, mulch was redistributed to planting sites in the medium duty truck (15.7 $l^{-100\,km}$) that transported 5 t (GW) per load. The low- and high-emission scenarios assumed travel distances of 16.1 and 32.2 km per load by trucks whose fuel efficiencies were 15.7 $l^{-100\,km}$ and 22.4 $l^{-100\,km}$, respectively.

The CO_2 released through decomposition of mulch derived from aboveground biomass and roots from removed trees was calculated. Calculations conservatively assumed that 100% of the CO_2 stored in mulch was released to the atmosphere the same year that the tree was removed or pruned.

Based on a review of the literature (Cairns et al., 1997; Drexhage and Colin, 2001; Harmon et al., 2009; Melillo et al., 1989; Scheu and Schauermann, 1994; Silver and Miya, 2001; Smith et al., 2011), it was assumed that roots accounted for 22% of total tree biomass and 80% of the CO_2 stored in belowground root biomass was immediately released from the dead tree roots to the atmosphere. This is a conservative assumption because it will take several years for tree roots to decompose.

The second scenario was based on the MTLA program's use of wood residue as feedstock for a bioenergy plant. Chips and logs from pruned and removed trees were transported 32.2 km round trip to the staging area in the box dump and medium duty trucks (15.7 $l^{-100\,km}$, CNG), where they were ground. The same 77% conversion efficiency and biomass processing constants that were used for the wood chip scenario were applied to the bioenergy scenario. After processing the chips were loaded into heavy duty trucks and transported an average of 436 km round trip (approximately 600 round trips annually) to a bioenergy plant in Dinuba, CA. It was assumed 10% of return trips involved a backhaul. Transport emissions were calculated annually as the product of the biomass moved (kg DW) and the transport coefficient (0.061 kg CO_2 per kg DW). The transport coefficient was based on total annual diesel emissions of 4922 t CO_2 and total biomass fuel consumption of 80,626 t. On-site emissions were calculated annually as the product of the feedstock consumed (kg DW) and the diesel fuel consumption coefficient (0.0047 kg CO_2 per kg DW). The on-site diesel fuel emissions coefficient was based on the ratio of 376 t CO_2 emitted from diesel consumption to 80,626 t of biomass fuel consumed. After accounting for the plant's 7111 MWh parasitic load, net displaced electricity was 0.823 MWh t^{-1} DW of biomass consumed. It is assumed that all wood residue was converted into CO_2 during wood combustion. The Dinuba plant sold its electricity to Pacific Gas & Electric, whose utility emission factor was 395 kg CO_2 MWh^{-1}.

The third scenario assumed that urban wood residues can find secondary market value when manufactured into wood products such as benches, picnic tables and other building materials (Bratkovich, 2001). This strategy delays the release of CO_2 into the atmosphere for the lifetime of the product. The lumber scenario only applied to the tree after it was removed because all pruned wood was small and chipped.

MacFarlane (2007) reported that about 60% of urban lumber is of merchantable size. Here it was assumed that 40% of the removed tree (1325 kg DW) was chipped and transported in the box dump truck, while the remaining logs (1989 kg) were transported to a saw mill in a medium duty truck (15.7 $l^{-100\,km}$, CNG). Chips were processed into mulch assuming the same 77% conversion efficiency and biomass processing constants that were applied in the other scenarios. The medium duty truck with 5 t (GW) capacity redistributed mulch to the planting sites and wood products to the retail sites after processing (16.1 km per load to and from the processing site). Lacking CO_2 emissions estimates for urban saw timber an emissions rate of 12 kg CO_2 m^{-3} was assumed from the literature for sawn wood (Buchanan and Levine, 1999). Average wood density was 480 kg m^{-3}. Mulch was assumed to immediately decompose with 100% of the stored CO_2 released to the atmosphere, while 80% of the CO_2 stored in the dead tree roots was released.

Results

Selection of high- and low-emitting vehicles and equipment

Emissions of CO_2 from high-emitting vehicles and equipment (Hi-E scenario) were nearly three times greater than for the low-emitting vehicles and equipment (Lo-E scenario). Assuming base equipment RTs and vehicle travel distances, total emissions over the 50-year period were 151.0 kg and 53.1 kg for the Hi-E and Lo-E scenarios, respectively (Table 1). Equipment emissions accounted for 81.6% and 84.2% of total CO_2 for the Hi-E and Low-E scenarios.

Assuming the Low-E scenario, crown reduction pruning (43.6 kg) and tree removal and stump grinding (35.5 kg) were the largest source activities. Carbon dioxide emissions for tree production (6.3 kg), inspection (2.6 kg) and planting (0.1 kg) were modest. Inspection became a more important source of CO_2 emissions (14.5 kg) for the Hi-E scenario because of substantially increased vehicle emissions.

Operational efficiency of vehicles and equipment

Emissions associated with Low OE scenarios were two to three times greater than for High OE scenarios. Assuming Low-E vehicles and equipment and safety pruning, CO_2 emissions over the 50-year period totaled 91.0 kg and 36.3 kg for the Low OE and Hi OE scenarios, respectively (Table 2). These values increased to 253.5 kg and 101.5 kg for Hi-E vehicles and equipment. Operating equipment more efficiently by reducing RTs was estimated to lower total emissions by 61%, or 48.6 kg and 129.9 kg for the Low-E and Hi-E equipment when conducting safety pruning. These potential equipment emission reductions nearly doubled with crown reduction pruning. Potential equipment emission reductions from reduced RTs were greatest for tree pruning, removal and stump grinding activities, which together accounted for over two-thirds of total equipment emissions. Reducing vehicle distance traveled was estimated to lower total emissions by about 54%, or 6.2 kg and 22.1 kg for the Low-E and Hi-E vehicle scenarios, respectively. Potential vehicle emission reductions were greatest for inspection, tree removal and tree production activities.

Reducing the amount of aboveground woody biomass removed during each prune from 20% to 10% resulted in a 24% to 46% reduction in total CO_2 emissions. Considering pruning emissions only for the Low-E, Base OE scenario, estimated CO_2 emissions from crown reduction pruning (43.6 kg) were five times greater than from safety pruning (8.5 kg) for the 50-year period (Table 2). The difference was primarily due to greater equipment emissions.

Irrigation water

Emissions of CO_2 for low, medium and high tree irrigation scenarios in Los Angeles totaled 0.82, 1.08 and 1.34 t CO_2, respectively for 50 years. Respective volumes of potable water use were 1476, 1937 and 2399 kl.

Utilization of tree residue as mulch, bioenergy and wood products

Converting tree residue to wood products resulted in the least net CO_2 emissions, while converting it to mulch released the most. The removed tree (pruned residue was used as mulch) contained 3.14 t of aboveground biomass (DW), of which 1.99 t (60%) was of merchantable size for wood products. Transporting tree residue to the processing site resulted in 16.0 kg CO_2 emissions. Processing chips from pruning into mulch (20.6 kg) and redistributing mulch to tree planting sites (4.2 kg) released 24.8 kg CO_2. Converting sawlogs into solid-sawn lumber, kiln drying and transporting to retail sites released 51.8 kg CO_2. The total amount of CO_2 released by these processes was 92.5 kg. Decomposition of mulch released 2433.0 kg CO_2. Decomposition of the dead tree's roots released 1372.2 kg. Approximately −1988.8 kg CO_2 was stored in the tree's merchantable biomass. Assuming this amount of CO_2 remained

Table 1
Carbon dioxide emissions (kg) over 50 years for equipment and vehicles used to grow a single tree in low- and high-emission scenarios with base operating efficiencies (OE, equipment run-times and vehicle travel distances).

Life stage	Lo-E scenario			Hi-E scenario		
	Equip	Vehicles	Total	Equip	Vehicles	Total
Tree production	4.6	1.7	6.3	11.3	4.1	15.4
Inspection	0.0	2.6	2.6	0.0	14.5	14.5
Planting	0.0	0.1	0.1	2.5	0.3	2.8
Prune-safety	7.4	1.1	8.5	25.6	2.3	27.9
Prune-crown reduction	41.4	2.2	43.6	126.5	4.6	131.1
Remove-grind stump	32.7	2.8	35.5	83.8	6.5	90.3
Total (with safety prune)	44.7	8.4	53.1	123.2	27.8	151.0
Total (with crown red. prune)	78.6	9.5	88.1	224.1	30.1	254.2

Table 2
Carbon dioxide emissions (kg) over 50 years for equipment and vehicles used to maintain a single tree in Lo-E and Hi-E scenarios with High, Base and Low operational efficiencies (OE).

Life stage	Lo-E scenario			Hi-E scenario		
	Hi OE	Base OE	Low OE	Hi OE	Base OE	Low OE
Tree production	6.3	6.3	6.3	15.4	15.4	15.4
Inspection	1.6	2.6	3.7	8.7	14.5	20.4
Planting	0.1	0.1	0.2	1.4	2.8	5.5
Prune-safety	4.3	8.5	13.1	14.4	27.9	42.4
Prune-crown reduction	21.1	43.6	67.2	64.9	131.1	201.7
Remove-grind stump	24.0	35.5	67.8	61.5	90.3	169.8
Total (with safety prune)	36.3	53.1	91.0	101.5	151.0	253.5
Total (with crown red. prune)	48.0	98.1	132.8	161.5	224.8	369.1

stored in the wood products for 50 years, it partially offset emissions. Net emissions from converting the removed tree biomass into mulch and wood products, plus root decomposition were 1908.9 kg CO_2.

Emissions associated with converting pruned and removed tree residue into bioenergy occurred at several steps. Transporting the removed tree residue to the processing center released 16.0 kg CO_2. Handling and grinding the material into chips released 51.4 kg. Transporting chips to the bioenergy plant released 155.8 kg and on-site emissions added 15.5 kg. Total emissions were 238.7 kg CO_2. Combustion of the wood and decomposition of the dead tree roots released 4683.5 kg and 1372.2 kg, respectively. Bioenergy displaced 2.1 MWh of electricity, equivalent to avoided release of −829.7 kg CO_2. Net emissions from converting the removed tree biomass into bioenergy were 5464.6 kg.

Over the course of 50 years the modeled tree was pruned nine times. Safety prunes removed a total of 958.4 kg of biomass (DW) and crown reduction prunes removed 1916.8 kg. Net CO_2 emissions associated with bioenergy obtained from pruned biomass were 1195.7 kg and 2391.4 kg for the safety and crown reduction prunes, respectively.

Transporting the chips and saw logs from the removed tree to the processing center in two vehicles was estimated to release 16.0 kg CO_2. On-site emissions by equipment such as the tub grinder (32.7 kg) and vehicles (6.9 kg) totaled 39.6 kg. Transporting mulch to planting sites released 8.0 kg CO_2. The total emissions by equipment and vehicles were 63.6 kg. Decomposition of mulch and the dead tree's roots released 4683.5 kg CO_2 and 1372.2 kg, respectively. Emissions associated with converting the removed tree's biomass into mulch and decomposition totaled 6119.3 kg CO_2. Total CO_2 emissions for safety and crown reduction pruning were 1375 kg and 2750 kg.

Biomass and CO_2 stored

After 50 years the California sycamore was estimated to have a dbh and height of 78.8 cm and 22.9 m, respectively. It contained 3314.7 kg of aboveground biomass (DW) and 934.7 kg belowground. This amount converted into −7797.7 kg CO_2 (negative number indicates removal from atmosphere). The uncertainty associated with the mean estimates of tree dimensions and CO_2 stored increased with tree age. Using 95% prediction intervals ($\alpha = 0.05$) from the tree growth equations, lower and upper dbh and height at 50 years were 40.6 cm and 117.0 cm and 21.1 m and 24.8 m, respectively. The lower and upper intervals for CO_2 stored were 1500 kg and 21,058 kg, respectively.

CO_2 balance

The total amount of CO_2 released as percentage of amount stored by the California sycamore tree over 50 years was small for equipment and vehicles (0.5–3.3%), and large for irrigation water use (10.6–17.2%) and tree residue use (24.5–78.5%) (Table 3). The CO_2 totals are negative because CO_2 emissions are less than the amount stored as biomass (−7.798 t).

The cradle-to-grave CO_2 balance adds emissions from water and tree residue to equipment and vehicle emissions. For the Highest Emission Case, which combined the Hi-E, Lo OE, high water

Table 3
Carbon dioxide emissions (t), net removed (calculated as the sum of the amount stored as biomass [−7.798 t] and the amount released) and total CO_2 released as percentage of amount stored by the California sycamore tree over 50 years for selected scenarios. Low-E, Hi OE = Low Emissions, High Operational Efficiency. Hi-E, Lo OE = High Emissions, Low Operational Efficiency.

Scenario	Emissions	Net CO_2 removed	Emissions as % stored in tree
Low-E, Hi OE	0.036	−7.761	0.5
Hi-E, Lo OE	0.254	−7.544	3.3
Low Water	0.823	−6.974	10.6
High Water	1.338	−6.459	17.2
Wood utilization[a]	1.909	−5.889	24.5
Biopower[a]	5.465	−2.333	70.1
Mulch[a]	6.119	−1.678	78.5

[a] For removed tree only.

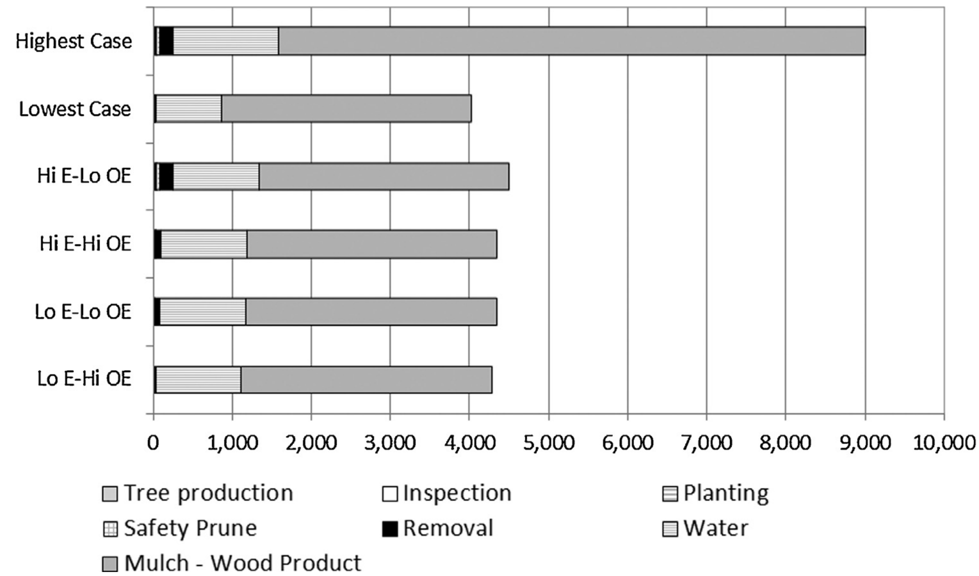

Fig. 2. Carbon dioxide emissions (kg) over 50 years for equipment and vehicles used to maintain the California sycamore tree for six scenarios. The Highest Case assumes maximum emission scenario for vehicles and equipment (Hi E-Lo OE), high water use and all chips from pruning and removal used as mulch. The Lowest Case assumes minimum emission scenario for vehicles and equipment (Lo E-Hi OE), low water use and merchantable removed tree residue converted to wood product and all chips from pruning and removal used as mulch. The remaining four scenarios all assume moderate irrigation water use and tree residue converted to wood products and mulch. Hi E-Lo OE = High Emissions, Low Operational Efficiency, Hi E-H OE = High Emissions, High Operational Efficiency, Lo E-Lo OE = Low Emissions, Low Operational Efficiency. Lo E-Hi OE = Low Emissions, Low Operational Efficiency.

use and mulch scenarios, total emissions (9.002 t) exceeded CO_2 stored (−7.798 t), resulting in net emissions of 1.204 t (Fig. 2). The Lowest Emission Case resulted in net removal of −3.768 t CO_2 over the 50-year period. Net emissions for the four cases that assumed moderate water use and tree residue converted to wood products ranged from −3.293 t to −3.510 t for the 50-year period.

Discussion

This study used lifecycle assessment applied over 50 years for a California sycamore tree to compare CO_2 emissions associated with different decisions by arborists in terms of equipment and vehicle choices, operational efficiencies, irrigation water applied and the fate of wood residue from pruning and tree removal. There are four key findings. In Los Angeles, where ET demand and the emission factor for irrigation water were both large, the amount applied had a substantial effect on net emissions (Table 3). Converting residue from the removed tree to wood products that delayed CO_2 emissions for many years resulted in substantially lower net CO_2 emissions than did converting it into bioenergy or mulch. Arborists can reduce CO_2 emissions threefold by selecting energy efficient equipment and vehicles and twofold by operating them at maximum efficiency. It was possible to achieve a fivefold emissions reduction for pruning by simply removing 10% rather than 20% of the aboveground biomass during each prune. These findings contribute new knowledge on the relative impacts of arboricultural practices on CO_2 emissions, identify leverage points where opportunities to reduce emissions are greatest and suggest need for new research.

Comparison of findings with other studies

This study found that vehicle and equipment emissions ranged from 0.5% to 3.3% of the CO_2 stored in tree biomass for the 50-year period assuming safety pruning (Table 3). A study in Leipzig, Germany projected carbon footprints over 50 years for several design and maintenance scenarios applied to a 2.16 ha green space (Strohbach et al., 2012). Assuming slow tree growth, tree planting and maintenance CO_2 emissions were only 2.2% and 4.1% of total net CO_2 stored in trees after 50 years, for low and high mortality scenarios respectively. Average annual CO_2 emissions for the Sacramento, California region's six million existing trees were estimated at 9422 t (McPherson, 1998), 3% of the total estimated CO_2 sequestered and avoided emissions. In the MTLA LCI (McPherson and Kendall, 2014), vehicle and equipment emissions alone accounted for 4.9% of projected reductions from CO_2 stored in tree biomass plus avoided emissions. These results indicate that the vehicle and equipment emissions projected for scenarios in this study are of the same order of magnitude as reported elsewhere. Typically, these emissions are less than 10% of the CO_2 stored in an urban tree assuming high rates of survival.

One important difference between this analysis and the case study findings reported by Luck et al. (2014) pertains to the magnitude of emissions from equipment and vehicles. This study found equipment emissions accounted for 83% and vehicles 17% of total CO_2 released, while Luck et al. (2014) found that 14 vehicles were responsible for 80% of direct CO_2 emissions. Vehicle fuel efficiencies were similar in both studies. This difference could be attributed to longer travel distances (41 and 71 km per day per vehicle) for the arboriculture company, but it is impossible to determine because the number of trees treated were not reported. Additional research is needed to characterize vehicle and equipment usage for different types and sizes of tree care companies.

Irrigation water use

In this study the irrigation scenarios were for California sycamore receiving low, moderate and high amounts of irrigation based on measured whole tree transpiration from another study. The calibrated K_c values ranged from 0.09 to 0.15, much lower values than typically reported. For example, K_c for California sycamore in the South Inland Valley region is reported as moderate (0.4–0.6) (Costello and Jones, 1994). Lower K_c values here may reflect actual water use in the landscape when soil moisture is less than field capacity. The higher K_c values of 0.4–0.6 guide irrigation scheduling to insure that soil moisture is not limiting transpiration and tree growth. Other factors that may explain the discrepancy in K_c values include tree roots obtaining ground water and the possibility that actual CPA, which was not reported by McCarthy and Pataki (2010), was less than the CPA assumed based on the growth equation for 37 cm dbh street trees in Claremont.

Modeled average daily water use ranged from 80.9 l to 131.4 l for the low and high water use scenarios, and included losses due to irrigation inefficiencies. These amounts are comparable to the 79.9–129.8 l of whole tree water use measured for California sycamore street trees during summer in Los Angeles (McCarthy and Pataki, 2010). Emissions of CO_2 associated with these water use scenarios were substantial, accounting for 10.6% to 17.2% of the amount stored over the tree's 50-year life (Table 3). These emissions do not bracket the possible range for all trees because some species may require and receive more water than California sycamore, and others less. Therefore, tree selection and irrigation management are key leverage points for arborists in Los Angeles, to the extent that they have control over these practices.

It is important to acknowledge that while irrigation water is a major CO_2 emission source in the Los Angeles region, it may not be elsewhere. Los Angeles has relatively high ET demands during hot, dry summers, and a very high emission factor for potable water. The latter reflects the large amount of electricity required to pump water to Los Angeles, and for treatment and distribution. For example, the energy intensity for outdoor water uses in Northern California (13.25 MWh Ml^{-1}) is 32% of the value for Southern California (42.06 MWh Ml^{-1}) (Navigant Consulting, 2006). In climates where trees do not require regular irrigation CO_2 emissions are negligible.

Strategies to reduce irrigation emissions include selecting trees to plant that require less water and managing irrigation more efficiently. Relatively few field and lysimeter studies have measured tree water use. In his review, Costello (2013) reports evaluations for only 17 tree species. In many cases, species performed well at irrigation levels less than 25% ET_0, a finding confirmed for a number of species in Arizona (Connellan, 2013; Schuch, 2014). Further research is needed on the water needs of landscape species.

Improving irrigation efficiency has great potential for conserving water and reducing CO_2 emissions, but is complicated because of the variety of techniques used to irrigate trees. Key issues include watering to recharge deeper soil layers, use of widely spaced drip systems to reduce losses from evaporation and runoff, and zoning of irrigation so that the specific water needs of trees are satisfied (Connellan, 2013). Use of soil moisture probes provides data for more precise irrigation scheduling. Harvesting and banking of stormwater in the subsoil during winter can insure that moisture is adequate for the summer and minimize the use of potable water for irrigation (Symes and Connellan, 2013).

Under drought conditions in Adelaide, Australia, infrastructure was constructed to transport reclaimed water to the city's parks and gardens (Brindal and Stringer, 2013). However, the treated effluent had elevated levels of sodium and many of the soils were sodic. Plants with low tolerance to salinity were adversely affected. Hence, an integrated perspective is needed; one that considers effects on soil and plant health, as well as water conservation and CO_2 emissions.

Wood products

These findings indicate that reclaiming lumber from removed urban trees substantially reduces CO_2 emissions compared to converting it into bioenergy or mulch, assuming long-term CO_2 storage in wood products. Although secondary wood manufacturers and artisans are increasingly seeking out urban saw logs, markets are not well-established and knowledge is sparse (Cassens and Makra, 2014). Urban tree removal is considerably more expensive than forest logging because of the extra skill, time and equipment involved. Removed trees are usually widely dispersed, composed of different species and quality is highly variable. The supply of urban wood is inconsistent, spiking when drought, pests, storms or other disturbances cause large losses. Urban trees often have an abundance of character wood that contains knots, insect damage, stain and other characteristics that are not desired in higher grades of construction lumber. These features add uniqueness to finished products that appeal to custom wood manufacturers and home woodworkers. Despite growing demand, the high costs of harvesting and processing urban lumber are likely to confine it to specialty markets. There are many examples of successful programs that recycle trees into wood products (Cesa et al., 2003), but specialty markets are not uniformly robust. Research that identifies the current supply of urban wood residue, its utilization rate and product demand are fundamental to estimating realistic impacts of hardwood products on CO_2 storage in the future (Bratkovich et al., 2011).

Bioenergy

As communities strive to reduce their carbon footprints and waste disposal costs there is increasing interest in energy from renewable resources such as wood waste. National surveys of urban tree residue estimated that 14.5–35.5 million t of tree biomass (GW) is produced annually and only about 3% is burned for energy (Bratkovich et al., 2008). At the local scale, in Gainesville, FL the urban forest (12.2 km^2) was estimated to produce a sustainable supply of 48,800 t of green biomass annually, enough to meet 5.3% of the required feedstock for a new 100 MW bioenergy plant (Timilsina et al., 2014). In St. Paul, MN the utility operates a combined heat and power plant that consumes 272,000 t of wood chips annually, primarily sourced from urban tree removals (Bratkovich et al., 2008).

Although converting urban wood residue into biomass energy has potential to foster economic development, lower disposal costs and reduce dependence on fossil fuels, it faces many challenges. The biggest challenge is that projects need to be financially viable investments. Recommendations to optimize investment value include geographically clustering bioenergy producers and wood manufacturers to improve efficiency by increasing supply and reducing fuel transportation distances (Zoet et al., 2013). Creative non-grant funding methods, such as low interest loans to cover up-front capital costs of projects, can be effective. Incorporating bioenergy from urban tree biomass will require new commitments within the utility industry and with partners to address research needs, new biomass technologies, sustainable fuel supplies and delivery and development of traditional and non-traditional markets (e.g., carbon offset markets). Although arborists can play a leadership role in developing partnerships that promote bioenergy, they have little direct control over such markets. Hence, bioenergy cannot be considered a key leverage point for most arborists.

Equipment and vehicle selection and operation

Equipment fuel consumption and CO_2 emissions are proportional to the engine's kilowatts and run time. Chippers release the most emissions with the exception of stump grinders in several removal scenarios (Fig. 3). Chippers with higher kilowatt engines can usually process larger wood than can smaller machines. Strategies with potential to improve chipper performance include (1) match chipper size to the size of wood processed, (2) reduce RT by batching residue and (3) reduce amount of biomass pruned.

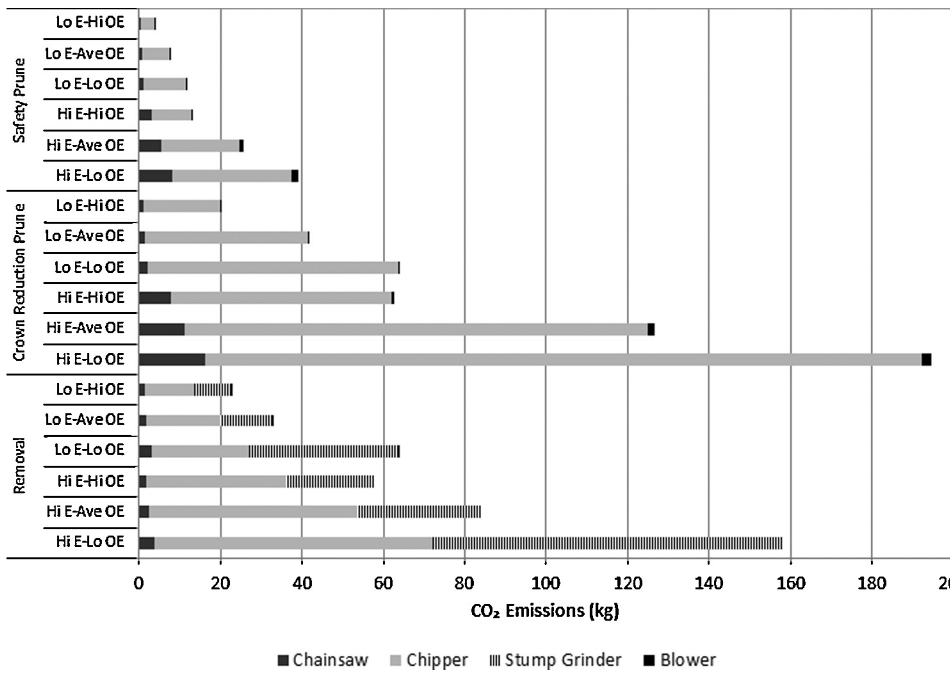

Fig. 3. Equipment emissions of CO_2 (t) released over 50 years for pruning of the modeled tree and for its removal at 50 years.

Stump grinding operations are straightforward with little opportunity for increasing efficiency. Matching the size and power of the stump grinder to the task is the best option for reducing emissions. Emissions from chainsaws are small relative to large engine equipment. Hand saws or electric chainsaws powered by batteries that are charged by the chipper can reduce fuel use. Although there are limits to potential emission reductions from heavy equipment such as chippers and grinders, there is potential for innovations associated with alternative fuels and lighter materials.

Vehicle emissions are related to engine fuel efficiency, distance traveled and the type of fuel consumed. Increasing fuel costs are compelling many cities and tree care companies to gradually convert their vehicle fleets. Hybrid sedans now commonly replace trucks for inspection and survey work. Fleet fuel efficiency can be improved by using lighter trucks with improved fuel efficiency, and lower-carbon fuels such as CNG and biodiesel. Similarly, new technologies such as on-board GPS units map out the most efficient travel routes and can reduce travel times. Vehicle emissions reductions can be achieved by using these technologies, as well as concentrating jobs in the same areas, thereby reducing travel distances.

Future research

It is important to recognize that this study's findings are constrained by its many underlying assumptions. For example, crew, equipment and vehicle configurations can vary widely. Travel distances and equipment RTs can differ depending on locations and job types. The availability and economic feasibility of using existing milling and bioenergy facilities is constantly changing. Although the assumptions used in this study may not replicate the situation of any one tree care company at one time, they do provide a baseline set of conditions from which field studies and modeling work can be extended. There is need for more emission inventories of tree care companies to better understand source distributions. These data are fundamental to validating emission models and identifying the most effective strategies for companies to reduce emissions while remaining competitive.

Conclusions

A key leverage point for arborists in Los Angeles is tree selection and irrigation water management. In this study CO_2 emissions for low and high irrigation scenarios accounted for 10.6% to 17.2% of the amount stored in tree biomass over the 50-year life. Because of differing employment geographies and scopes of work, not all arborists can influence tree selection and irrigation.

Converting residue from removed trees to wood products that delay CO_2 emissions for many years or bioenergy are secondary leverage points. Although potential CO_2 reductions are substantial compared to mulch that entirely decomposes, markets for recycled wood products and bioenergy feedstock are not uniformly robust. Arborists can work together locally and form the partnerships needed to create business clusters, financial incentives and enabling policies that support a vibrant wood products industry.

Most arborists have some control over the types of equipment and vehicles they use. However, emissions from these sources are relatively small, here found to account for less than 5% of the CO_2 stored in the tree over 50 years. Nevertheless, the arborist's decisions and practices can substantially reduce these emissions. For example, converting from high- to low-emitting equipment and vehicles reduced emissions nearly threefold. Reducing travel distances and equipment run-times cut emissions twofold. Reducing the amount of aboveground biomass pruned from 20% to 10% every five years lowered pruning emissions fivefold. Moreover, trees allowed to develop with regular but minimal pruning will be less prone to pests and structural failure than will trees that are too heavily pruned (Harris et al., 1999). These findings suggest that there are ample opportunities for arborists to reduce their carbon footprints and lower operating costs while improving human health and well-being in their communities through professional tree care.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ufug.2015.04.004

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